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From identification towards exploitation of geothermal reservoir: concepts and experience

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Exploration

- Continental
- Regional
- Concessional

Future Developments towards exploitation

- Case studies
- Analogue sites

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WP3 / 6

Chapter 1 of Best Practice Handbook:

Site investigation and Reservoir Characterization

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UGR and EGS reservoirs: Definition

Lower temperature limit is set by the current limitations in conversion technology

UGR (Unconventional Geothermal Resources):

- use of non-conventional methods for exploring, developing and exploiting geothermal resources that are not economically viable by conventional methods

EGS (Enhanced Geothermal Systems):

- Engineered to improve hydraulic performance

Introduction

- Identifying UGR and EGS reservoirs is not easy because:
  - They often leave only indirect traces on the surface
  - Temperature must be sufficiently high to allow electricity production
  - Permeability must reach a certain threshold in order to minimize pumping efforts
  - Characterization of the permeability of the potential reservoir is *a priori* not possible

- A clear identification and characterization of the reservoir is essential because:
  - It reduces exploration costs
  - It minimizes the probability of finding a non productive reservoir

Background
Thermal power (productivity) of a plant

$$P_{THERM} = Q \cdot \left[\rho c_P \right]_f \cdot \left(T_{PROD} - T_{REINJ} \right)$$

Temperature field:

- increases generally between 20 K – 30 K km^{-1}
- At specific locations temperature gradient > 100 K km^{-1}
- Most important factor for economic viable geothermal system
- Target production temperature from efficiency of conversion technology (Minimum ~85℃ - 100℃).
- marks the necessary drilling depth
- drilling costs increase non-linearly with greater depth

Background
Thermal power (productivity) of a plant

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Flow rate:

- productivity of a geothermal system is increased by higher flow rates.
- permeability varies in a broad range from < $10^{-18}m^2$ up to > $10^{-12}m^2$.
- Large reservoir permeabilities often yield natural convection patterns
- typical operation flow rates between 10 kg/s up to >100 kg/s
- Too high flow rates would dramatically increase the pumping power

Focus preferentially on areas with

- high natural permeability.
- high temperature

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Background
Concept of individual entry points

Best Practice Handbook Chapter 1 proposes a scale-dependant approach.

- It must be adapted to the considered geo-environment.
- Experience must be learned from previous success or failures.

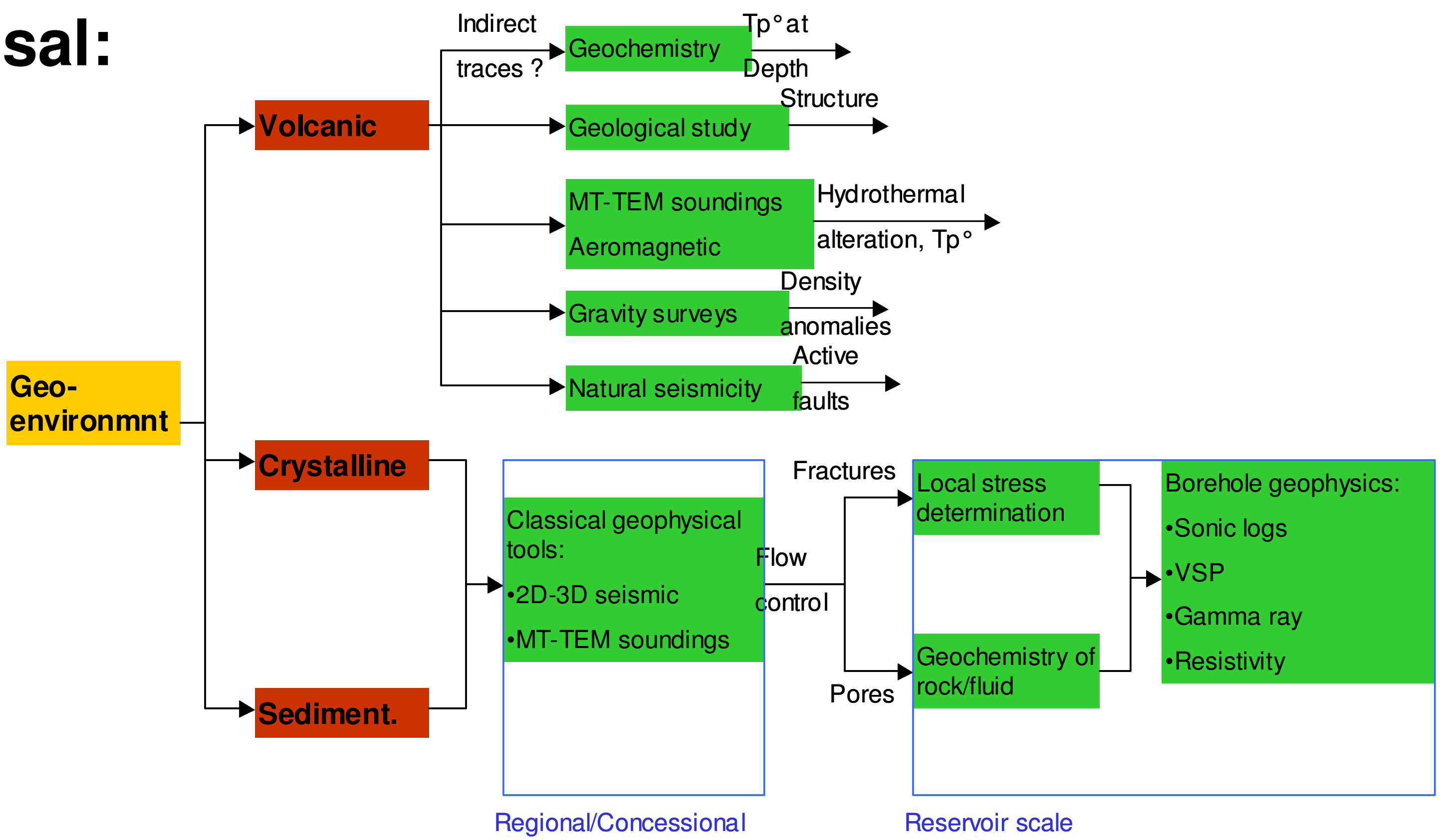
European scale
Regional scale
Local scale
Reservoir scale

Academic level
Application level
Engineer level
Decider level

Exploration

Can the geo-environment prescribe the investigation methodology?

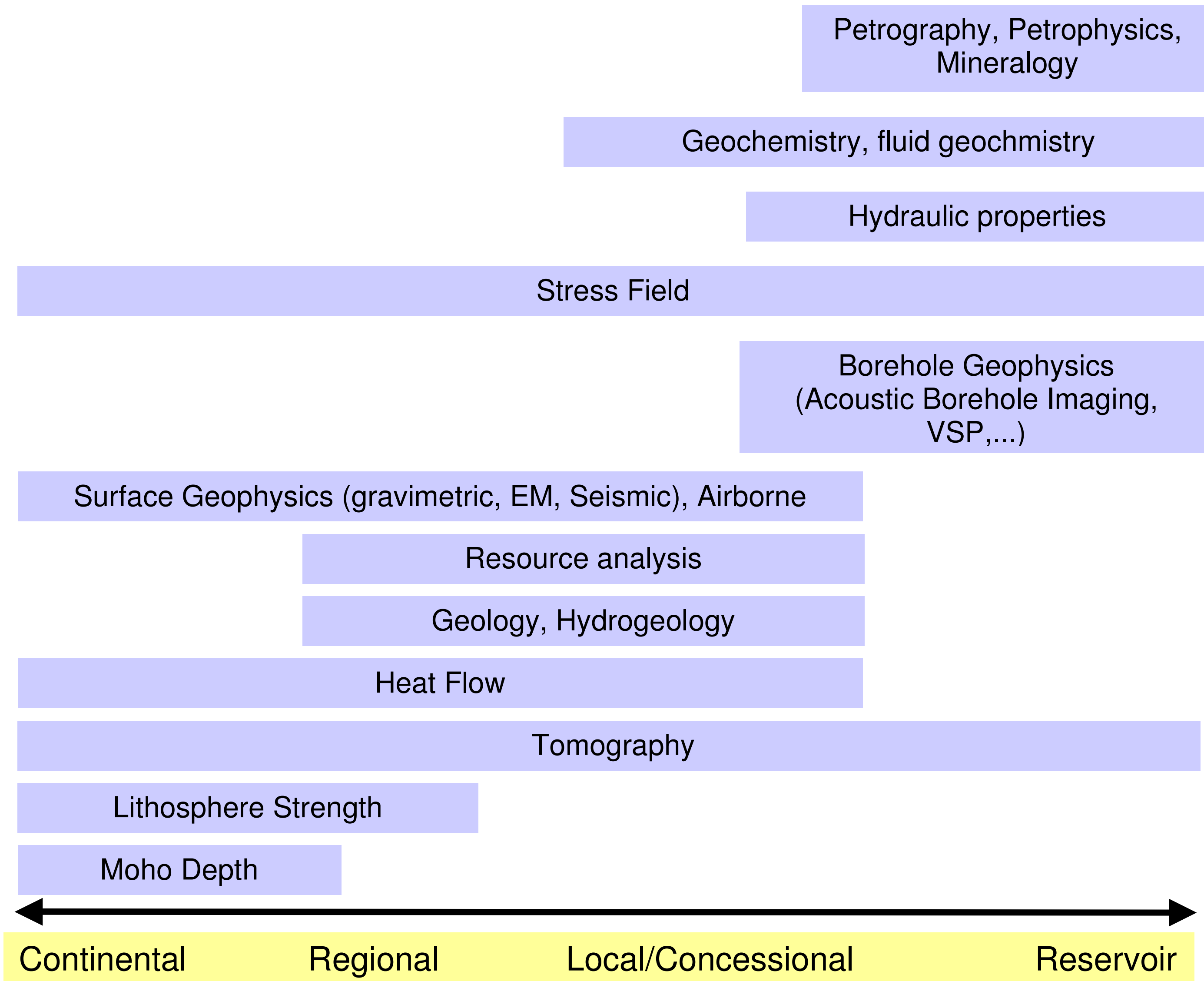
Proposal:



Not possible to describe a procedure for individual geo-environments

Exploration

Investigations are scale-dependent



1. Continental scale

Identification of potentially interesting regions of interest is based on:

- Thermal field at greater depths (>10km)
  - from tomography
  - From thermal modeling
  - Task: Identify thermal anomalies
- Deformation regime of the crust
  - from passive stretching models
  - Extensional regimes can be of high interest
- Stress regime (neo-tectonics)
  - from data cross-checking.
  - Strike-slip regimes and extensional are the most interesting

Geo-environment cannot be defined at that scale

Task: Identify regions of interest

2. Regional scale

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- Heat flow analysis
  - temperature gradient
  - well data
- Seismic methods:
  - focal mechanisms of earthquake
  - smaller scale seismic events.
- Large-scale gravimetry:
  - geometric trends of deep layers
- 2D/3D seismic profiles
  - defining a geological model of reservoir
- Electromagnetic prospection:
  - apparent resistivity of rocks
    (link to geothermal reservoir not clearly established)
- Remote sensing
  - identification of regional structures
  - characterization of temperature fields

Task: Identify concessional areas

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Soultz-sous-Forêts EGS Site: Regional-Scale Temperature Anomaly

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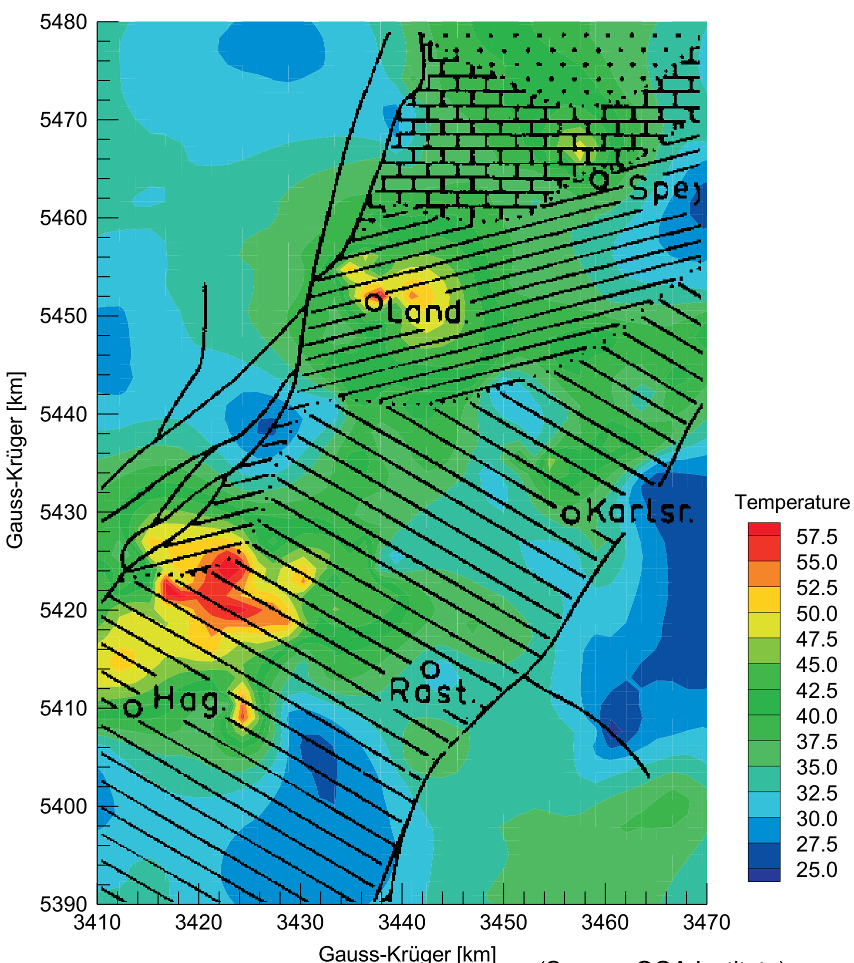
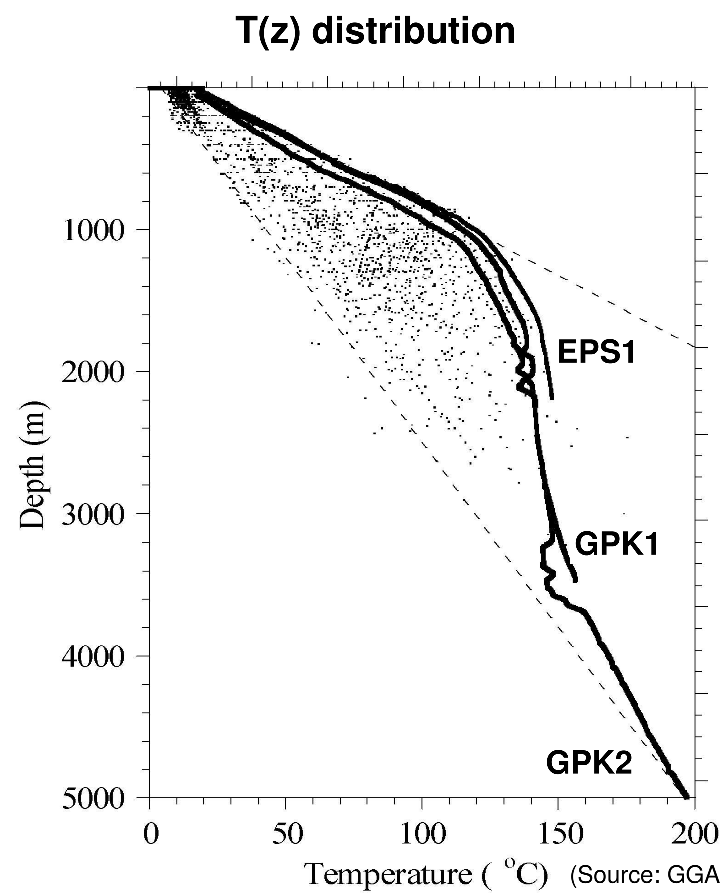
Northern Upper Rhine Graben Temperature in 500m depth



(Source: GGA Institute)

Temperature distribution in Upper Rhine Graben



(Source: GGA Institute)

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Key methods in exploration: Gravimetry on Regional Scale

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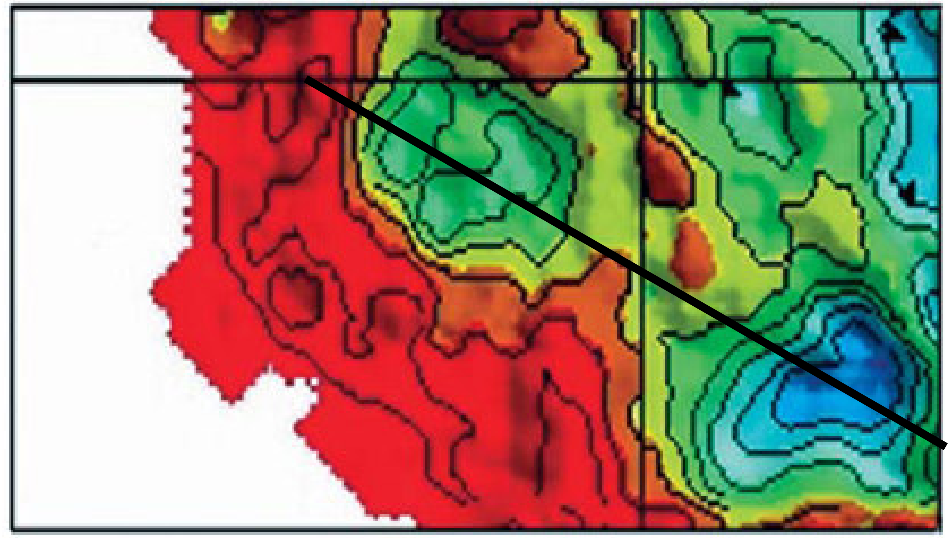
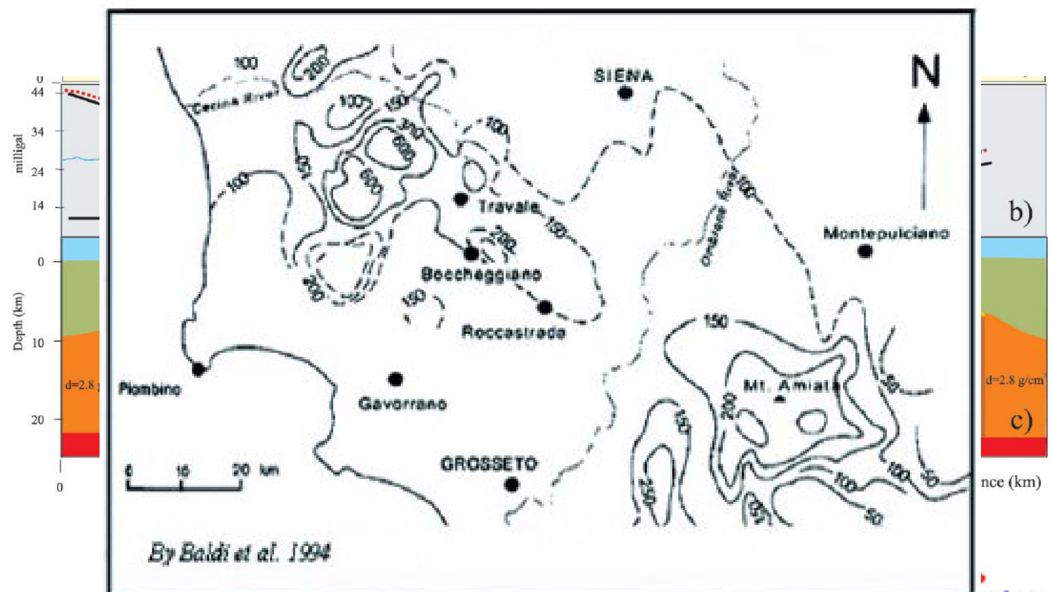
Lardello-Travale / Mt. Amiata

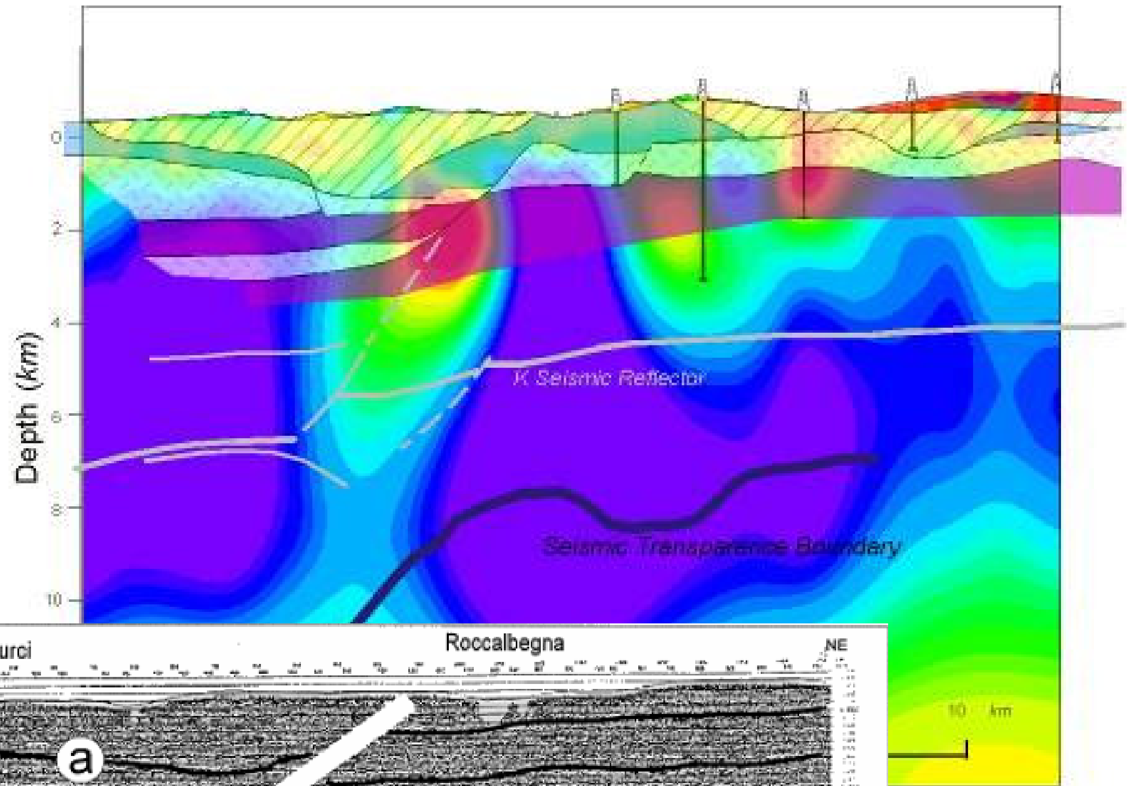
- stripped gravity data

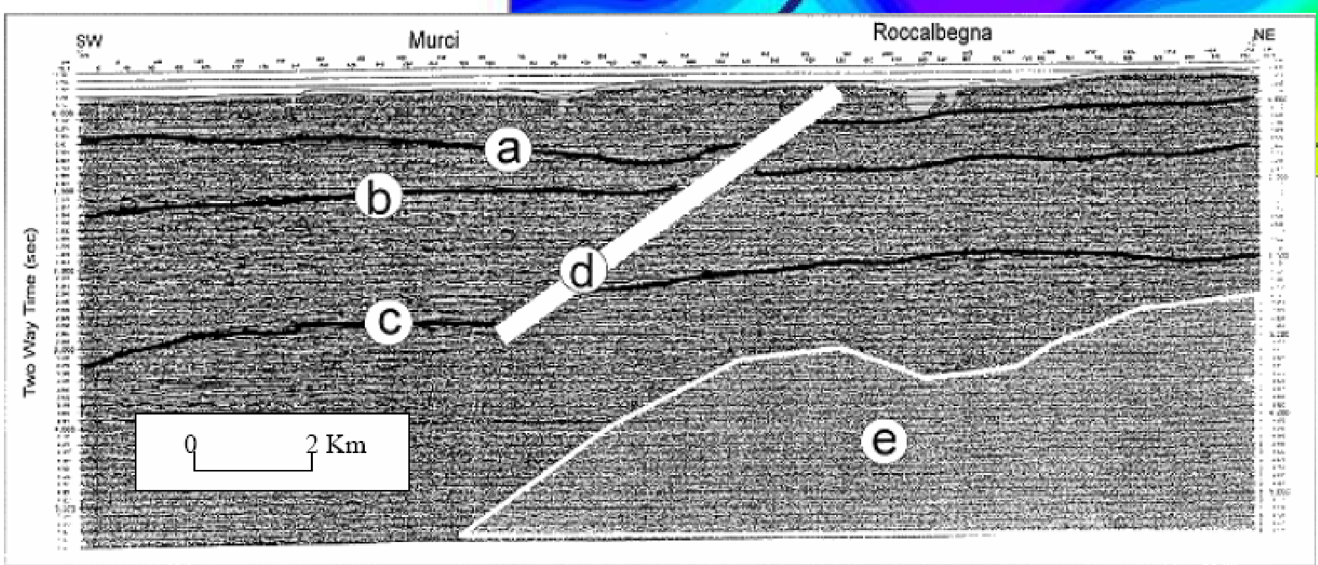


- Heat Flow Pattern



Key methods in exploration:
MT & Seismic Profile on Regional Scale





3. Concessional scale

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Classical geophysical tools:

- 2D/3D seismic for geological mapping/identification of fault zones.
- Electromagnetic methods (MT-TEM-DC).
  Geothermal reservoirs ✍ Low resistivity zone ?
- Gravimetry. Geothermal reservoirs can have a gravimetric signature
- Gas flux measurement
- Geothermometers (circulation depth of water), …

Resource potential analysis:

- integration of geological, hydrological and geophysical data
- Estimation of energy recoverable from the reservoir.
- Cross-checking with infrastructure / areas of demand
- Economic viability of the system.

Task: Identify reservoirs

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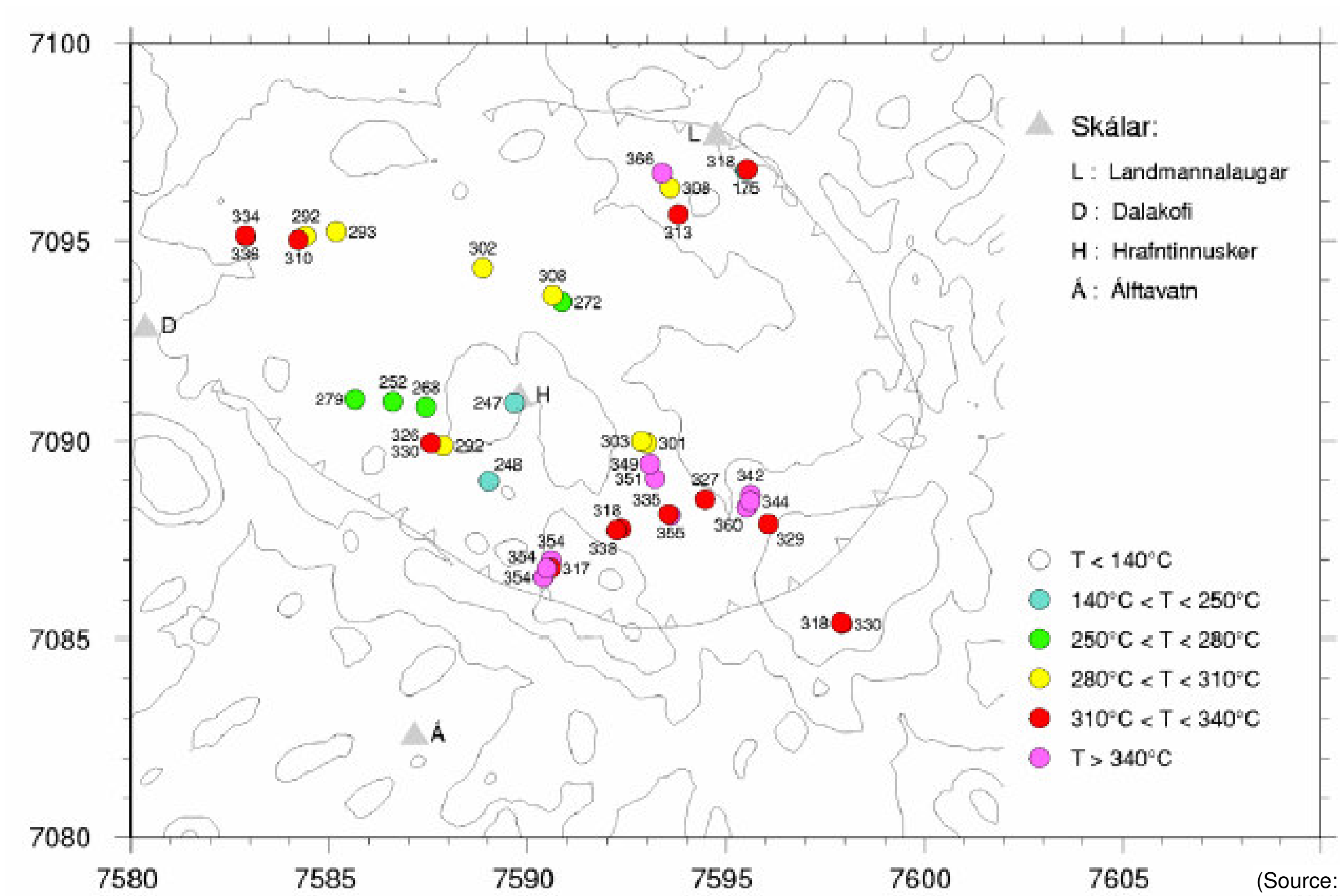
Geochemistry (Geothermometer)
Torfajökull, Iceland CO_2 / N_2 –gas

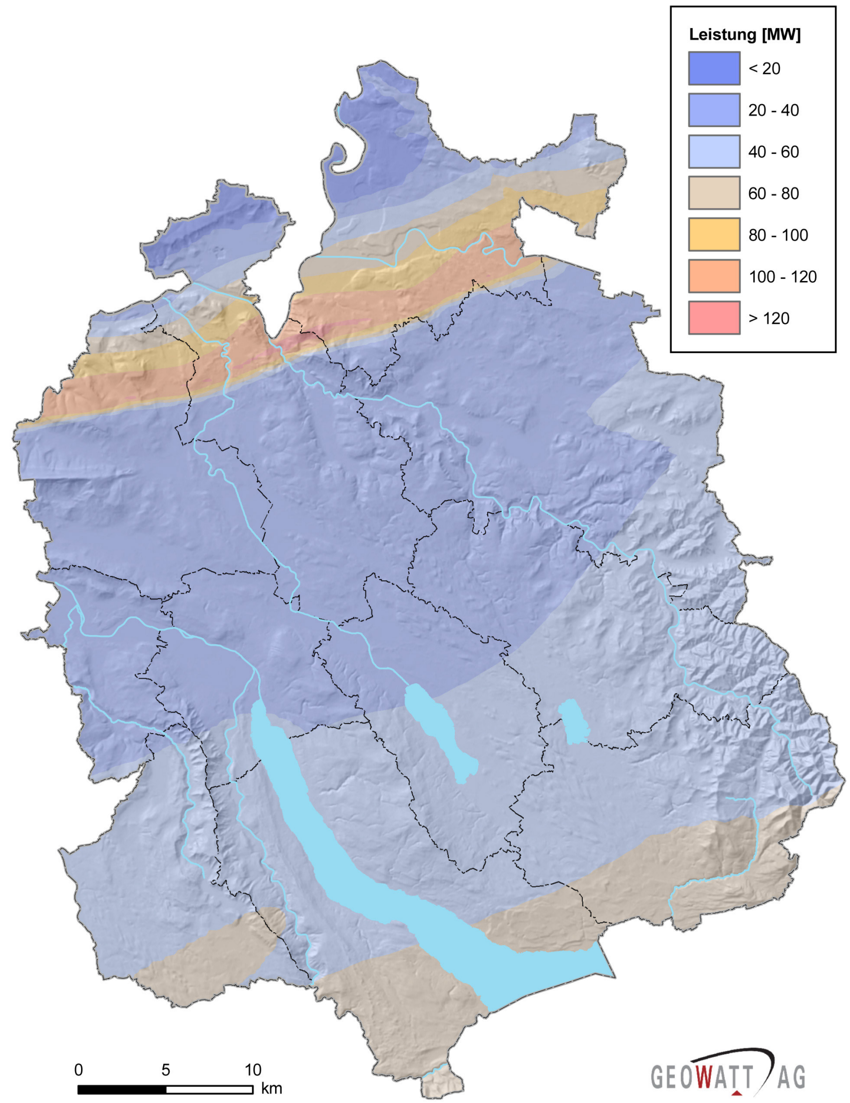


(Source: ISOR Institute)

Resource potential analysis
Canton Zurich (Crystalline Basement)

Key Parameters:

- Geometry of the aquifer
- Temperature at depth
- Hydraulic conductivity



4. Reservoir scale

Field geology

- fracture orientation by outcrop analysis
- alteration of reservoir by cores and sample analysis
- ...

Well geophysics

- Vertical seismic profile, allows identification of structures at a distance from the well
- Borehole acoustic imaging and sonic log provides information about fractures crossing boreholes
- Borehole gravimetry can help defining conditions into the reservoir
- Gamma ray and resistivity logs provide information on the material surrounding the borehole

Local stress determination

- stimulation strategy

Conceptual model can be built, and assumptions verified with reservoir numerical model.

Conceptual Model: Mutnovsky (Kamchatka)

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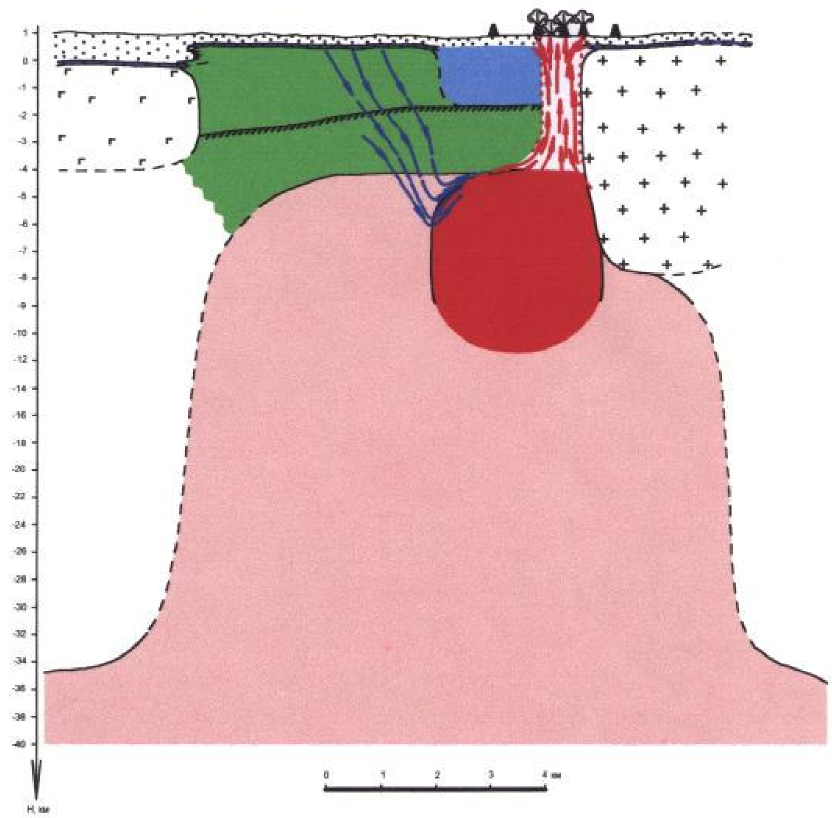
Vapor-hydrothermal spreading in porous sediments

Revealed from

- Aeromagnetic
- gravity,
- Direct Current (DC),
- Transient Electro-magnetic (TEM)
- Magneto-telluric (MT)



Exploration Summary

Down-scaling workflow approach:

I. Continental scale approach
OBJECTIVE: Qualitative overview over the geothermal potential in a continent
- I.a. Definition of interesting Regions
- I.b. Thermo-mechanical crustal models
- I.c. Neotectonics

II. Regional scale (e.g. Rhine Graben Pannonian basin)
OBJECTIVE: Quantification and mapping of the geothermal potential in a geological region
- II.a. Large scale Geophysics studies
- II.b. Remote sensing

III. Concessional scale (e.g. typical 50x50km)
OBJECTIVE: Site location of an exploration well
- III.a. Geochemistry
- III.b. Intermediate scale Geophysics studies
- III.c. Resource potential
- III.d. Cross-checking with areas of demand for economy

IV. Reservoir scale (e.g. typical 2x2km)
OBJECTIVE: Site location of further wells
- IV.a. 3D geology
- IV.b. Well investigation and small-scale geophysics
- IV.c. Geothermometer
- IV.d. Fluid and rock geochemistry
- IV.e. Local stress
- IV.f. Conceptual model and reservoir modelling

Experience learned from the past

Electromagnetic methods (MT-TEM soundings):

- Essential in volcanic environment (defines the degree of alteration of the reservoir). Ex: Iceland
- Can help defining extension of the reservoir in other geo-environments (but link between reservoir and resistivity not clear yet). Ex: Larderello

2D-3D seismic:

- Very powerful geological mapping tool.
- Weak responses from permeable zones
- Does not necessarily help understanding nature of the system
- High costs

Experience learned from the past

Resource potential analyse

- Helps quantifying and defining potential target zones. Ex: Switzerland, Limagne

Microseismicity monitoring

- Many techniques newly developed (multiplet clustering, focal mechanism inversion...) helps understanding reservoir. Essential for location of further wells. Ex: Soutlz
- Are seismic clouds flow paths ?

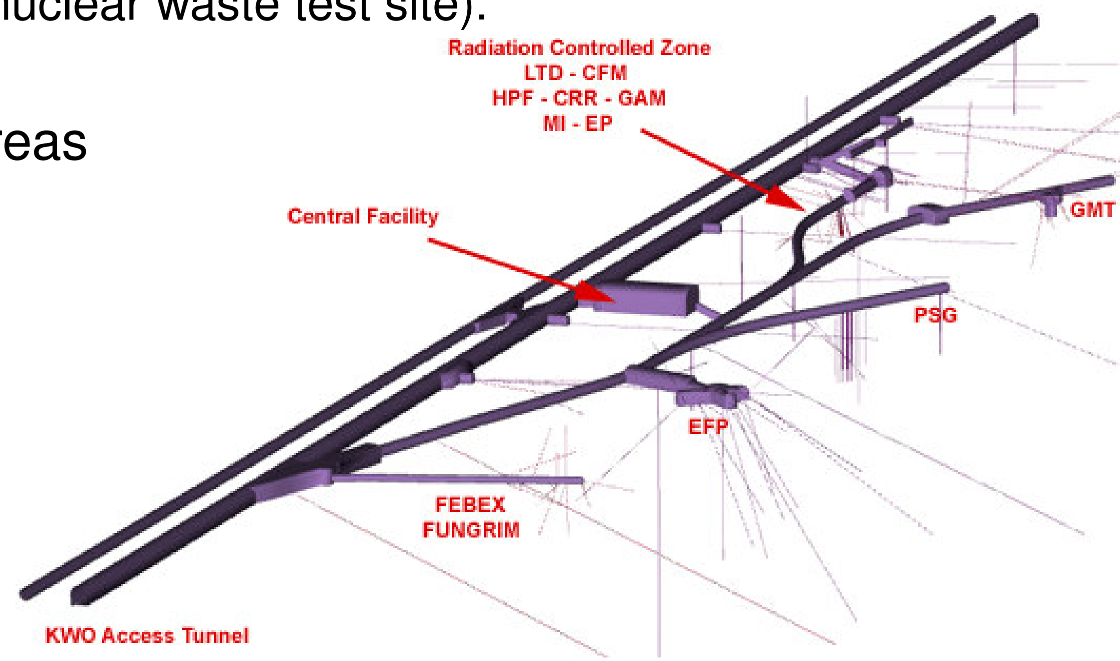
Well-scale geophysics

- Helps defining stress field (Tensile fracturing,...)
- information on the local geology.
- VSP results in Soultz?

Advantage of Analogue Sites

Analogue sites:

- defined by a set of common features in identical geo-environment.
- Examples for analogue sites are
  - outcrops (observation of e.g. mechanical conditions on fracture),
  - representative geothermal sites (e.g. Soultz; Gross Schönebeck)
  - test sites (e.g. Grimsel nuclear waste test site).
- Exist in other research areas
  - Nuclear waste research
  - CO2 sequestration



Conclusion

Different Methods have been successfully applied

Individual entry points to the investigation of EGS

Analogue sites are important for:

- Improvement of existing tools
- Development of new tools

Complexity in Earth science is different from typical engineering approaches.

- Necessity of more experience

ENGINE allowed to assemble the wide-spread knowledge